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# THE ISOSCALAR QUADRUPOLE STRENGTH DISTRIBUTION ABOVE 10 MeV IN $^{40}$Ca

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From angular correlation measurements of $\alpha_0$ decay to the $^{36}$Ar ground state, the isoscalar E2 strength distribution between 10 and 16 MeV in $^{40}$Ca has been found to be concentrated in the interval $E_x$ = 12.5–15.5 MeV and to exhaust about 12% of the EWSR in the $\alpha_0$ channel and about $(45^{+10}_{-15})$% if extrapolated to all channels.

The existence of a compact isoscalar quadrupole resonance (GQR) has been well established for nuclei with $A \geqslant 60$ (see e.g. refs. [1] and [2] and references therein). Most of the systematics on these resonances has been obtained from inelastic hadron scattering experiments. The GQR manifests itself as an approximately lorentzian shaped bump located at about $E_x = 65\,A^{-1/3}$ MeV, with a width (FWHM) varying from about 3.0 MeV for $A$ = 208 to about 5 MeV for $A$ = 90 and exhausting (50–100)% of the $T$ = 0, E2 energy weighted sum rule (EWSR). For light nuclei with $A < 40$ the $T$ = 0, E2 strength is distributed over a wide energy range, while in most cases only about 50% of the EWSR is exhausted in the giant resonance region ($E_x > 10$ MeV) [1].

The main experimental uncertainty arises from the fact that in inelastic hadron scattering experiments the bump due to giant resonance excitation is located on top of a continuum which can be due to processes like knock-out and multi-step reactions, excitation of higher multipole strength, and pickup–breakup processes [3–5]. In order to decompose the inelastic hadron spectrum into a resonance part and a continuum, one has to assume a certain shape for the nuclear continuum. The usual procedure is to join smoothly the continuum above and below the resonance bump. Especially for the part below the bump at the low excitation energy side, however, it is often difficult to estimate how big the continuum part really is because of threshold effects and the presence of many highly excited and partly overlapping states. Large errros up to ±25% can thus be introduced in the resonance strength [1].

A possible tool to disentangle the resonance from the underlying continuum is to measure the particle decay of these highly excited states. This method has been shown to be useful if there are decay channels into which the giant resonance decays much stronger than the underlying continuum, as is the case for the $\alpha$-decay channel for some light nuclei [6–9]. Similarly, it will be useful if the angular correlation pattern in one of the decay channels is characteristic of a well defined $J^\pi$ of the highly excited decaying state.

In this letter we describe the results of such a decay experiment for the energy region $E_x$ = 10–20 MeV in $^{40}$Ca. We concentrate on the region $E_x < 16$ MeV for which it was found that, under the experimental circumstances to be described, the $\alpha_0$ decay to the ground state of $^{36}$Ar exhibits an angular correlation pattern showing that it originates nearly exclusively from $J^\pi = 2^+$ decay. Making a reasonable assumption for the relative decay widths of other than $J^\pi = 2^+$ strength, we conlcude that $(60^{+15}_{-25})$% of the E2 EWSR must be present in $^{40}$Ca in the interval $E_x$ = 10–15.5 MeV, which is much more than has been found in previous inelastic hadron scattering experiments on $^{40}$Ca (see refs. [10] and [11] and references therein). Our results strongly suggest that in these previous experiments on $^{40}$Ca the contribution from the continuum for $E_x < 15$ MeV has been largely overestimated.

A beam of 120 MeV momentum analysed $\alpha$-par-

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ticles from the KVI cyclotron was used to bombard a $^{40}$Ca target of which the thickness of (880 ± 90) $\mu$g/cm$^2$ was determined from comparing the inelastic scattering yield for some low-lying sharp states with those of a previous experiment [10]. The $\alpha$-particle scattered over an angle of 12.5° ± 2.1° were detected with the QMG/2 magnetic spectrograph using a solid angle of $\Omega_s$ = 7.30 msr. The resolution was about $\Delta E$ = 75 MeV. Charged particles in coincidence with the inelastically scattered $\alpha$-particles were detected with a telescope consisting of a $\Delta E$, an $E$ and a veto solid-state counter of thicknesses of 15 $\mu$m, 2 mm and 1 mm, respectively. The solid angle of this telescope was defined by a circular opening of 4 mm diameter in a 2 mm thick brass collimator at a distance of about 45 mm from the target resulting in a solid angle of about $\Omega_t$ = 6 msr and an opening angle of about 5°. Coincidence measurements were performed for several telescope angles between 59° and 247° with respect to the beam direction, corresponding to the range −10° to 180° with respect to the recoil axis of the $^{40}$Ca nucleus. At each telescope angle $\alpha$-decay to the $^{36}$Ar $0^+$ g.s. and the $J^\pi = 2^+$ first excited state and proton decay to the $^{39}$K $J^\pi = 3/2^+$ g.s. and to the group of states with $J^\pi = 1/2^+, 1/2^-$ and $3/2^-$ could be clearly separated.

In the excitation energy region up to 16 MeV both the singles and the coincidence spectra show various structures, a well known feature already observed in previous experiments [9,10]. The region $E_x < 15.5$ MeV was divided into intervals as given in table 1; for each interval the angular correlation pattern for $\alpha_0$ decay was determined. These intervals were chosen in such a way that they approximately correspond to the structures which can be observed in the singles $(\alpha,\alpha')$ spectra [10]. The results are shown in fig. 1, where $P$ is defined by

$$P(\Omega_t, E_x) = \frac{\partial^3\sigma_{\alpha_0}(\Omega_t,\Omega_s,E_x)}{\partial\Omega_t\partial\Omega_s\partial E_x}\left(\frac{\partial^2\sigma_s(\Omega_s,E_x)}{\partial\Omega_s\partial E_x}\right)^{-1}, \tag{1}$$

with $\sigma_{\alpha_0}$, $\sigma_s$ being the coincidence and singles cross

Table 1
Results of the fits to the $\alpha_0$ angular correlations shown in fig. 1 and corresponding $J^\pi = 2^+$ sum rule strength.

| Interval | | Fit parameters expressed as fraction of the singles cross section | | | % E2 EWSR | |
|---|---|---|---|---|---|---|
| centroid (MeV) | width (keV) | $0^+$ | $2^+$ | $3^-$ | $\alpha_0$-channel $S_{\alpha_0}$ | total $S_T$ |
| 10.05 | 221 | | 0.15 ± 0.02 | <0.02 | 0.2 | 1.3 |
| 10.28 | 242 | | | | | |
| 10.52 | 242 | | | | | |
| 10.75 | 242 | | | | | |
| 11.00 | 263 | | 0.11 ± 0.01 | 0.007 ± 0.005 | 0.3 | 2.2 |
| 11.44 | 571 | | 0.15 ± 0.02 | <0.002 | 0.7 | 3.7 |
| 11.95 | 458 | <0.02 | 0.17 ± 0.02 | | 1.1 | 4.5 |
| 12.33 | 305 | 0.03 ± 0.02 | 0.30 ± 0.03 | | 1.1 | 3.3 |
| 12.75 | 544 | <0.01 | 0.27 ± 0.03 | | 1.8 | 6.4 |
| 13.41 | 760 | <0.01 | 0.24 ± 0.02 | | 2.4 | 9.7 |
| 14.09 | 584 | 0.017 ± 0.015 | 0.31 ± 0.03 | | 3.4 | 9.7 |
| 14.64 | 518 | <0.001 | 0.16 ± 0.02 | | 1.6 | 9.7 |
| 15.02 | 279 | 0.06 ± 0.02 | 0.35 ± 0.04 | | 2.2 | 5.4 |
| 15.30 | 279 | <0.02 | 0.17 ± 0.02 | | 1.0 | 5.4 |
| 15.77 | 644 | | | | | |
| 16.26 | 341 | | | | | |
| 16.99 | 555 | | | | | |
| 17.26 | 574 | | | | | |
| 18.79 | 2468 | | | | | |
| | | | | | total $S_{\alpha_0}$ = (15.8 ± 1.0)% | $S_T$ = (61 ± 5)% |

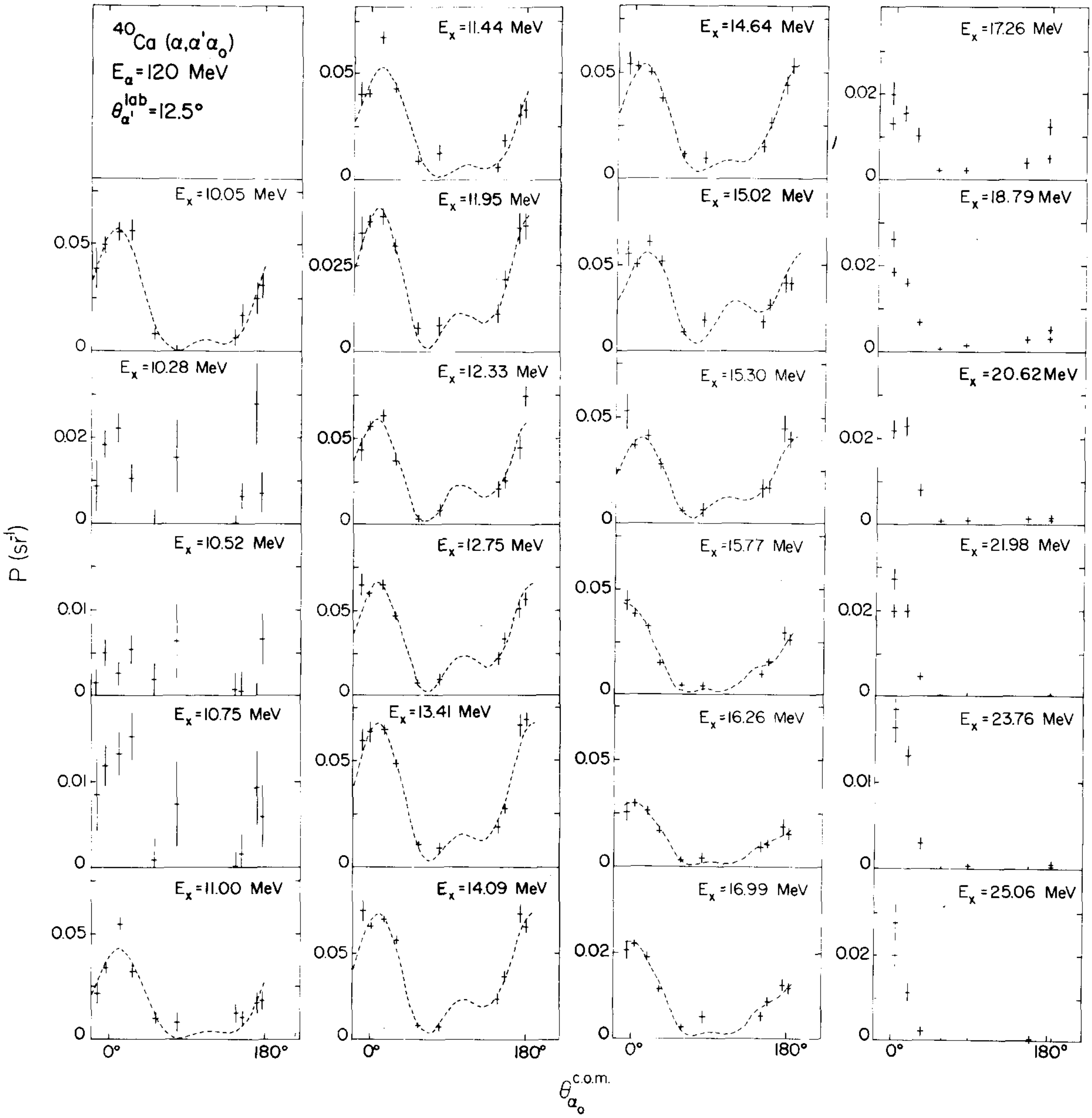


Fig. 1. The $\alpha_0$ angular correlations for the intervals listed in table 1. The quantities $P(\mathrm{sr}^{-1})$ are defined by formula (1) (see text). The lines are fits obtained by adding coherently the two contributions resulting from the decay of two different $J^\pi$ strengths. The $J^\pi$ values and their relative contributions are given in table 1.

sections at an energy $E_x$, respectively. The fits are calculated with the program ANGCOR [12], using at most two different interfering intermediate states with a given $m$-state population. These $m$-state populations were obtained from DWBA calculations with the program DWUCK, using standard optical model parameters [10]. The large opening angle of the spectrograph was taken into account by averaging the calculated angular correlation over the opening angle weighted with the DWBA cross section. Once the $J^\pi$

values of the two intermediate states are chosen, the only free parameter left for the fit is their respective contribution to the $\alpha_0$ decay. The fits shown are obtained with the parameters given in table 1. In these calculations it was assumed that the summation over the two intermediate states is coherent. In those cases in which on basis of the fits obtained a decision between coherent or incoherent summation could not be made it was found that the relative contributions of the $J^\pi$ states involved did not differ significantly for either of these assumptions.

The $J^\pi = 2^+$ cross sections $\partial^2\sigma_{\alpha_0}(\Omega_s, E_x)/\partial\Omega_s\partial E_x$ thus obtained were converted to $B_{\alpha_0}(E2, E_x)$ values, using radial moments [11] obtained from the geometry parameters of the real part of the optical potential [10]. For the calculation of $\widetilde{S}$, the total E2 sum-rule strength, the Fermi mass distribution of ref. [13] was used. Table 1 lists the values of $S_{\alpha_0}(E_x) = B_{\alpha_0}(E2, E_x) \cdot E_x/\widetilde{S}$ thus obtained. The errors shown are statistical only. In addition, the relative uncertainties in target thickness and other normalization factors are estimated at ±15%. Thus we find that for $E_x$ = 10.0–15.5 MeV about (15.8 ± 3.2)% of the $T$ = 0 E2 EWSR is exhausted in the $\alpha_0$ decay branch only.

The present results can be compared with those of previous decay work on $^{40}$Ca [14,15]. Youngblood et al. found that for the interval 12.5–15.3 MeV the $\alpha_0$ angular correlation pattern could be fitted quite well by assuming $J^\pi = 2^+$ decay and that this decay accounted for ≈20% of the singles cross section [14]. This is in very good agreement with our value of 25% averaged over the same interval. But it is very different from the result of Moalem et al. who found for the region 13.5–15.6 MeV an $\alpha_0$ decay branching ratio of 0.48 ± 0.08 [15].

In order to calculate the total E2 strength the same procedure should be applied in principle to all possible decay channels $\bar{c}$ with $\bar{c} = \alpha_1, \alpha_2, ..., p_0, p_1, ...$ . But since for all these decay channels many different $L$-values can and will contribute, their angular correlations are in general not specific for $J^\pi = 2^+$ decay. Thus on the basis of these correlations one cannot decide whether they also originate predominantly from $J^\pi = 2^+$ intermediate states, as is the case for the $\alpha_0$ decay branch, or whether they originate from some nuclear continuum which could also be excited in this excitation energy interval by the $(\alpha, \alpha')$ process. However, from the $\alpha_0$ angular correlations it can be argued that nearly the whole singles cross section for $E_x$ = 11.0–15.5 MeV is due to $J^\pi = 2^+$ excitation and that nearly no continuum can be present.

Such continuum could be due to excitation of $J > 2$ strength in a one-step process, to multi-step processes, to knock-out reactions or particle pick-up by the projectile and subsequently break-up. The last process can be excluded by considering the kinematics of the pickup–breakup process. Knock-out processes manifest themselves in a forward–backward asymmetry with respect to the recoil axis [9]. In the interval under consideration they only occur to some extent in the $p_0$ channel [9] but even there their contribution to $\Gamma_{p_0}$ is negligibly small.

On basis of the $\alpha_0$ angular correlations, the presence of a substantial amount of $J > 2$ strength can also be excluded, provided that such strength would also decay statistically. Calculations show that in that case the branching ratio $(\Gamma_{\alpha_0}/\Gamma_T)$ for $J > 2$ decay would be similar to that for $J^\pi = 2^+$ decay. Thus such strength would manifest itself in the correlations shown in fig. 1 and especially around $\theta = 0°$ and 180°, where it would cause the correlation pattern to decrease much steeper with increasing $\theta$ than the characteristic pattern for $2^+$ decay. From the fits shown in fig. 1 one can estimate that such $J > 2$ strength could contribute at most 10% to the $\alpha_0$ decay branch and thus, assuming statistical decay, also to the singles cross section.

Similar arguments can be used with respect to multi-step processes. In the extreme case of many steps, one would again expect a statistical decay. Moreover, because of the expected more or less random $m$-state population, such processes would result in approximately isotropic angular distributions, which again can be excluded on basis of the $\alpha_0$ angular correlations. Few-step processes will lead to an $\alpha_0$ angular correlation which is symmetric around 90° and may peak at 0° (180°). In the extreme case of all spins perpendicular to the recoil axis, it will look like a $(\sin\theta)^{-1}$ distribution. In intermediate cases it will have an isotropic component, both of which can be excluded for the $\alpha_0$ branch. Thus, by making the reasonable assumption that $(\Gamma_{\alpha_0}/\Gamma_T)$ would be approximately similar for $J^\pi = 2^+$ strength and for the underlying continuum we are led to the conclusion that such a continuum should be weak in the interval

$E_x$ = 0–15.5 MeV. Only the unlikely case that multistep processes would lead to predominantly $2^+$ excitation while maintaining an $m$-state population similar to the one-step excitation, cannot be excluded.

To a very good approximation the $\alpha_0$ branching ratio for $J^\pi = 2^+$ strength is then given by $\Gamma_{\alpha_0}/\Gamma_T = \int P(\Omega_T)\,d\Omega_T$. The total E2 strength in the interval $E_x$ can be calculated from $S_T = S_{\alpha_0}(\Gamma_T/\Gamma_{\alpha_0})$ and is also shown in table 1. We find that $(60^{+15}_{-25})$% of the $T$ = 0, E2 EWSR is present in the interval $E_x$ = 10.0–15.5 MeV, where the quoted uncertainty includes a contribution from the fits (±5%), from the uncertainty in target thickness and other normalization factors (±10%) and from the possible contributions of $J > 2$ strength (−10%). As shown in table 1 most of this strength is concentrated in the interval 12.5–15.5 MeV. This result is very different from what is quoted for $^{40}$Ca in the literature (see refs. [10] and [11] and references therein), where a compact GQR is found to be located around $E_x$ = 18 MeV, with a FWHM width of $\Gamma$ = 2.3 MeV and a strength corresponding to about 50% of the EWSR. Around $E_x$ = 14 MeV at most 20% of the EWSR has been found.

The present experiment suggest that the strength distribution is very different, about 45% concentrated around $E_x$ = 14 MeV and 50% or less around $E_x$ = 18 MeV. It is also very different from what has been suggested by the many calculations, mainly RPA ones, sometimes including (2p–2h) excitations, performed for $^{40}$Ca (see refs. [16–21] and references therein). All these calculations give concentrated E2 strength around $E_x$ = 18 MeV. Clearly our results make it necessary to reexamine the basic features, the single particle energies and the strength of the residual p–h interaction which are going into such calculations. Finally, one should remark, that the occurrence of $2^+$ strength at about $E_x$ = 14 MeV has been observed for many other nuclei in the f–p shell [22] and one wonders whether the approximately equal splitting of strength as observed here for $^{40}$Ca would not be a general feature of all nuclei in the f–p shell.

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